5. COMPOSTING

This chapter has been extensively revised since the first edition of this report. The revised chapter presents the results of an in-depth analysis to determine the net GHG impacts of composting yard trimmings and food discards. As research in the areas of erosion control, soil fertility, and bio-based products continues, we are likely to uncover additional GHG and other benefits of composting.

This chapter presents estimates of GHG emissions and sinks from composting yard trimmings and food discards.[1] The chapter is organized as follows:

Section 5.1 presents an estimate of potential CO_2 and CH_4 emissions from composting;

Section 5.2 quantifies the potential carbon storage benefits of applying compost to soils;

Section 5.3 presents net GHG emissions from composting; and

Section 5.4 discusses the limitations of this analysis.

Composting may result in (1) CH_4 emissions from anaerobic decomposition; (2) long-term carbon storage in the form of undecomposed carbon compounds; and (3) non-biogenic CO_2 emissions from collection and transportation of the organic materials to the central composting site, and from mechanical turning of the compost pile.[2] Composting also results in biogenic CO_2 emissions associated with decomposition, both during the composting process and after the compost is added to the soil. Because this CO_2 is biogenic in origin, however, it is not counted as a GHG in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*[3] (as explained in Section 1.4.2) and is not included in our accounting of emissions and sinks.

Our analysis suggests that composting, when managed properly, does not generate CH_4 emissions, but it does result in some carbon storage (associated with application of compost to soils), as well as minimal CO_2 emissions from transportation and mechanical turning of the compost piles. In order to maintain consistency with other chapters in this report, we selected point estimates from the range of emission factors—covering various compost application rates and time periods—developed in our analysis. The point estimates were chosen based on a "typical" compost application rate of 20 tons of compost per acre, averaged over three soil-crop scenarios. In terms of timing, the carbon storage values for the year 2010 were selected to be consistent with forest carbon storage estimates presented in Chapter 4 of this report. Overall, we estimate that centralized composting of organics results in net GHG storage of 0.05 MTCE/wet ton of organic inputs composted and applied to agricultural soil.

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[1] Although paper and mixed MSW can be composted, we did not analyze the GHG implications of composting them because of time and resource constraints.

[2] CO_2 emissions from delivery of compost to its final destination were not counted because compost is a marketable product, and CO_2 emissions from transportation of other marketable, finished goods to consumers have not been counted in other parts of this analysis.

[3] U.S. EPA. 2001. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1999*. U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation, Washington, DC. EPA-236-R-01-001.

5.1 POTENTIAL GREENHOUSE GAS EMISSIONS

Two potential types of GHG emissions are associated with composting: (1) CH_4 from anaerobic decomposition; and (2) non-biogenic CO_2 from transportation of compostable materials, and turning of the compost piles.

5.1.1 CH_4

To research the issue of CH_4 emissions, we first conducted a literature search for articles on CH_4 generation from composting. We found very few articles specifically addressing CH_4 emissions from composting published between 1991 and 1999,[4] and thus decided not to continue searching for earlier articles. Because CH_4 emissions from composting are addressed only occasionally in the literature, we contacted several composting experts from universities and the U.S. Department of Agriculture to discuss the potential for CH_4 generation, based on the nature of carbon flows during composting. Our CH_4 analysis is based on their expert opinions.

The researchers we contacted stated that well-managed compost operations usually do not generate CH_4 because they typically maintain an aerobic environment with proper moisture content to encourage aerobic decomposition of the materials. The researchers also noted that even if CH_4 is generated in anaerobic pockets in the center of the compost pile, the CH_4 is most likely oxidized when it reaches the oxygen-rich surface of the pile, where it is converted to CO_2. Several of the researchers commented that anaerobic pockets are most apt to develop when too much water is added to the compost pile. They noted that this problem rarely occurs because compost piles are much more likely to be watered too little rather than too much.

We concluded from the available information that CH_4 generation from centralized compost piles is essentially zero.

5.1.2 CO_2 from Transportation of Materials and Turning of Compost

This study estimated the indirect CO_2 emissions associated with collecting and transporting organics to centralized compost facilities, and turning the compost piles. We began with estimates developed by Franklin Associates, Ltd. (FAL) for the amount of diesel fuel required to (1) collect and transport 1 ton of organics[5] to a central composting facility (363,000 Btu) and (2) turn the compost pile (221,000 Btu).[6] We converted these estimates to units of metric tons of carbon equivalent (MTCE) per ton of organics, based on a carbon coefficient of 0.02 MTCE per million Btu of diesel fuel. This resulted in an estimate of 0.01 MTCE of indirect CO_2 emissions per ton of material composted in a centralized facility.

5.2 POTENTIAL CARBON STORAGE

We also evaluated the effect of compost application on soil carbon storage. We did not find information on carbon storage associated with compost derived specifically from yard trimmings or food discards. Nevertheless, it is reasonable to expect that these materials are basically homogeneous with respect to the fate of their stored carbon, even though their initial moisture and carbon content differs.

[4] Among the papers with pertinent information is that of H.J. Hellebrand, 1998, *Emission of Nitrous Oxide and other Trace Gases during Composting of Grass and Green Waste,* J. Agric. Engineering Research 69:365-375.

[5] Measured on a wet weight basis, as MSW is typically measured.

[6] Franklin Associates, Ltd. 1994. *The Role of Recycling in Integrated Solid Waste Management to the Year 2000* (Stamford, CT: Keep America Beautiful), pp. I-27, 30, and 31.

To develop carbon storage estimates for composted organics, we researched the processes that affect soil carbon storage, reviewed the results of experiments on the soil carbon impacts of applying organic amendments (e.g., compost, manure, biosolids, and crop residues), and interviewed experts on the potential carbon storage benefits of composting organics as compared to other methods of disposal. During this process, four hypotheses were proposed regarding the benefits of applying organics compost to soil:

(1) Many soils have been depleted in organic matter through cultivation and other practices. Adding compost can raise soil carbon levels by increasing organic matter inputs. Soils degraded by intensive crop production, construction, mining, and other activities lose organic matter when decomposition rates and removals of carbon in harvests exceed the rate of new inputs of organic materials. Adding compost shifts the balance so that soil organic carbon levels are restored to higher levels. Some of the compost carbon is retained by the system.

(2) Nitrogen in compost can stimulate higher productivity, thus generating more crop residues. This "fertilization effect" would increase soil carbon due to the larger volume of crop residues, which serve as organic matter inputs.

(3) The composting process leads to increased formation of stable carbon compounds (e.g., humic substances, aggregates) that then can be stored in the soil for long (>50 years) periods of time. Humic substances comprise 60-80 percent of soil organic matter and are made up of complex compounds that render them resistant to microbial attack.[7] In addition to humic substances, soil organic carbon may be held in aggregates (i.e., stable organo-mineral complexes in which carbon is bonded with clay colloids and metallic elements) and protected against microbial attack.[8]

(4) The application of compost produces a multiplier effect by qualitatively changing the dynamics of the carbon cycling system and increasing the retention of carbon from non-compost sources. Some studies of other compost feedstocks (e.g., farmyard manure, legumes) have indicated that the addition of organic matter to soil plots can increase the potential for storage of soil organic carbon. The carbon increase apparently comes not only from the organic matter directly, but also from retention of a higher proportion of carbon from residues of crops grown on the soil. This multiplier effect could enable compost to increase carbon storage by more than its own direct contribution to carbon mass accumulation.

Our research efforts did not yield any primary data that could be used to develop quantitative estimates of the soil carbon storage benefits of compost. Therefore, we developed modeling approaches to investigate the possible effects of compost application on soil carbon storage. Section 5.2.2 describes application of the CENTURY model to quantify soil carbon restoration and nitrogen fertilization associated with compost application to carbon-depleted soils. We conducted a bounding analysis, described in Section 5.2.6, to address the third hypothesis, incremental humus formation. Although several of the experts we spoke with cited persuasive qualitative evidence of the existence of a multiplier effect, we were unable to develop an approach to quantify this process. In that sense, our carbon storage estimates are likely to be conservative (i.e., understate carbon storage rates), at least for soils with high silt and/or clay content where this process is most likely to apply.

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[7] N. Brady and R. Weil. 1999. *The Nature and Properties of Soils* (Upper Saddle River, NJ: Prentice Hall).

[8] R. Lal et al. 1998. *The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect* (Ann Arbor, MI: Sleeping Bear Press, Inc).

Our analyses of soil carbon restoration, nitrogen fertilization, and incremental humus formation apply relatively simple models of very complex processes. These processes probably are controlled by a number of biological, physicochemical, and compost management factors, such as application (i.e., silviculture, horticulture, agriculture, and landscaping); application rate; regional and local climatic factors; soil type; and, to a lesser extent, compost feedstock (e.g., grass, leaves, branches, yard trimmings, food discards). In addition, the results are time-dependent, so the year in which benefits are assessed has an effect on the magnitude of carbon storage.

Note that the framework used here describes the soil carbon benefits of composting relative to landfilling and combustion. In all three management methods, yard trimmings are collected and removed from soils in residential or commercial settings. This removal may result in some loss of organic carbon from the "home soil." An estimate of the "absolute" soil carbon storage value would net out whatever loss occurs due to the removal of the yard trimmings. This effect is probably a negligible one, however, and we were unable to find empirical data on it. Because the decrement in carbon in "home soil" applies equally to all three management practices, and emission factors are intended to be viewed relative to other management practices (see Chapter 8), neglecting the carbon loss from the home soil does not compromise the validity of the results.

5.2.1 Modeling Soil Carbon Restoration and Nitrogen Fertilization

As mentioned above, this analysis included an extensive literature review and interviews with experts to consider whether the application of compost leads to long-term storage of carbon in soils. After determining that neither the literature review nor discussions with experts would yield a basis for a quantitative estimate of soil carbon storage, we evaluated the feasibility of a simulation modeling approach. We initially identified two simulation models with the potential to be applied to the issue of soil carbon storage from compost application: CENTURY[9] and the Rothamsted C (ROTHC-26.3)[10] model. Both are peer-reviewed models whose structure and application have been described in scores of publications. They share several features:

- Ability to run multi-year simulations;
- Capability to construct multiple scenarios covering various climate and soil conditions and loading rates; and
- Ability to handle interaction of several soil processes, environmental factors, and management scenarios such as carbon: nitrogen (C:N) ratios, aggregate formation, soil texture (e.g., clay content), and cropping regime.

Given the extensive application of CENTURY in the United States, its availability on the Internet, and its ability to address many of the processes important to compost application, we decided to use CENTURY rather than ROTHC-26.3.

5.2.2 CENTURY Model Framework

CENTURY is a Fortran model of plant-soil ecosystems that simulates long-term dynamics of carbon, nitrogen, phosphorus, and sulfur. It tracks the movement of carbon through soil pools—active, slow, and passive—and can show changes in carbon levels due to the addition of compost.

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[9] Metherell, A., L. Harding, C. Cole, W. Parton. 1993. CENTURY Agroecosystem Version 4.0, Great Plains System Research Unit Technical Report No. 4, USDA-ARS Global Climate Change Research Program, (Colorado State University: Fort Collins, CO).

[10] This model was developed based on long-term observations of soil carbon at Rothamsted, an estate in the United Kingdom where organic amendments have been added to soils since the 19th century.

In addition to soil organic matter pools, carbon can be found in surface (microbial) pools and in above- and below-ground litter pools. The above-ground and below-ground litter pools are divided into metabolic and structural pools based on the ratio of lignin to nitrogen in the litter. The structural pools contain all of the lignin and have much slower decay rates than the metabolic pools. Carbon additions to the system flow through the various pools and can exit the system (e.g., as CO_2, dissolved carbon, or through crop removals).

The above-ground and below-ground litter pools are split into metabolic and structural pools based on the ratio of lignin to nitrogen in the litter. The structural pools contain all of the lignin and have much slower decay rates than the metabolic pools. The active pool of soil organic matter includes living biomass, some of the fine particulate detritus,[11] most of the non-humic material, and some of the more easily decomposed fulvic acids. The active pool is estimated to have a mean residence time (MRT)[12] of a few months to 10 years.[13] The slow pool includes resistant plant material (i.e., high lignin content) derived from the structural pool and other slowly decomposable and chemically resistant components. It has an MRT of 15-100 years.[14] The passive pool of soil organic matter includes very stable materials remaining in the soil for hundreds to thousands of years.[15]

CENTURY does not simulate increased formation of humic substances associated with organic matter additions, nor does it allow for organic matter additions with high humus content to increase the magnitude of the passive pool directly. (Because CENTURY does not account for these processes, we developed a separate analysis, described in Section 5.2.6.)

CENTURY contains a submodel to simulate soil organic matter pools. Additional submodels address nitrogen, phosphorus, sulfur, the water budget, leaching, soil temperature, and plant production, as well as individual submodels for various ecosystems (e.g., grassland, cropland). The nitrogen submodel addresses inputs of fertilizer and other sources of nitrogen, mineralization of organic nitrogen, and uptake of nitrogen by plants.

5.2.3 Inputs

The CENTURY model simulates the long-term dynamics of various plant-soil ecosystems (e.g., grassland, agricultural land, forest, and savanna). The model uses a series of input files to specify modeling conditions: Crop, Harvest, Fertilization, Cultivation, Organic Matter Addition, Irrigation, Grazing, Fire, Tree Type, Tree Removal, Site, and Weather Statistics. A schedule file is used to specify the timing of events.

For this analysis, we developed a basic agricultural scenario where land was converted from prairie to farmland (growing corn) in 1921 and remains growing corn through 2030. We then evaluated more than 30 scenarios to examine the effect of several variables on soil carbon storage:

- Compost application rate and frequency;

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[11] Detritus refers to debris from dead plants and animals.

[12] The term "mean residence time (MRT)" is used interchangeably with "turnover time" and is the average time in which a unit (e.g., a carbon atom) resides within a "state" where there is both an input and an output. MRT is only strictly defined at steady-state (i.e., inputs = outputs), but as most soils systems have a continuing input of carbon and an approximately equal output through decomposition and transfer to other pools, MRT is often used to describe carbon dynamics in soils. Mathematically, it is the ratio of (a) mass in the pool to (b) throughput of carbon. For example, if a given carbon pool has a mass of 1,000 kg and the inflow is 1 kg/yr, the MRT is 1,000 kg / (1 kg/yr) = 1,000 yr.

[13] Metherell et al. 1993, Brady and Weil 1999.

[14] *Ibid.*

[15] *Ibid.*

- Site characteristics (rainfall, soil type, irrigation regime);
- Fertilization rate; and
- Crop residue management.

Compost application rates were adjusted using the organic matter (compost) files for each compost application rate included in our analysis. We compared the effect of applying compost annually for 10 years (1996-2005) at seven different application rates: 1.3, 3.2, 6.5, 10, 15, 20, and 40 wet tons compost/acre (corresponding to 60-1,850 grams of carbon per square meter).[16] We also investigated the effect of compost application frequency on the soil carbon storage rate and total carbon levels. We ran the model to simulate compost applications of 1.3 wet tons compost/acre and 3.2 wet tons compost/acre every year for 10 years (1996-2005) and applications of 1.3 wet tons compost/acre and 3.2 wet tons compost/acre applied every five years (in 1996, 2001, and 2006). The simulated compost was specified as having 33 percent lignin,[17] 17:1 carbon-to-nitrogen (C:N) ratio,[18] 60:1 carbon-to-phosphorus ratio, and 75:1 carbon-to-sulfur ratio.[19] We also ran a scenario with no compost application for each combination of site-fertilization-crop residue management. This scenario allowed us to control for compost application, i.e., to calculate the change in carbon storage attributable only to the addition of compost.

The majority of inputs needed to specify a scenario reside in the site file. The input variables in this file include the following:

- Monthly average maximum and minimum air temperature;
- Monthly precipitation;
- Lignin content of plant material;
- Plant nitrogen, phosphorus, and sulfur content;
- Soil texture;
- Atmospheric and soil nitrogen inputs; and
- Initial soil carbon, nitrogen, phosphorus, and sulfur levels.

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[16] The model requires inputs in terms of the carbon application rate in grams per square meter. The relationship between the carbon application rate and compost application rate depends on three factors: the moisture content of compost, the organic matter content (as a fraction of dry weight), and the carbon content (as a fraction of organic matter). Our inputs are based on values provided by Dr. Harold Keener of Ohio State University, who estimates that compost has a moisture content of 50 percent, an organic matter fraction (as dry weight) of 88 percent, and a carbon content of 48 percent (as a fraction of organic matter). Thus, on a wet weight basis, 21 percent of compost is carbon.

[17] Percent lignin was estimated based on the lignin fractions for grass, leaves, and branches specified by compost experts (particularly Dr. Gregory Evanylo at Virginia Polytechnic Institute and State University, and lignin fractions reported in M.A. Barlaz, "Biodegradative Analysis of Municipal Solid Waste in Laboratory-Scale landfills," EPA 600/R-97-071, 1997. FAL provided an estimate of the fraction of grass, leaves, and branches in yard trimmings in a personal communication with ICF Consulting, November 14, 1995. Subsequently, FAL obtained and provided data showing that the composition of yard trimmings varies widely in different states. The percentage composition used here (50 percent grass, 25 percent leaves, and 25 percent branches on a wet weight basis) is within the reported range.

[18] The C:N ratio was taken from Brady and Weil, 1999, *The Nature and Property of Soils: Twelfth Edition*, Prentice Hall.

[19] C:P and C:S ratios were based on the literature and conversations with composting experts, including Dr. Gregory Evanylo at Virginia Polytechnic Institute and State University.

Several sets of detailed site characteristics from past modeling applications are available to users. We chose two settings: an eastern Colorado site with clay loam soil and a southwestern Iowa site with silty clay loam soil. Both settings represent fairly typical Midwestern corn belt situations where agricultural activities have depleted soil organic carbon levels. The Colorado scenario is available as a site file on the CENTURY Web site;[20] Dr. Keith Paustian, an expert in the development and application of CENTURY, provided the specifications for the Iowa site (as well as other input specifications and results for several of the runs described here).

We also varied fertilization rate. As discussed earlier, one of our hypotheses was that the mineralization of nitrogen in compost could stimulate crop growth, leading to production of more organic residues, which in turn would increase soil organic carbon levels. The strength of this effect would vary depending on the availability of other sources of nitrogen. To investigate this hypothesis, we analyzed different rates of synthetic fertilizer addition ranging from zero up to a typical rate to attain average crop yield (90 lbs. N/acre for the Colorado site, 124 lbs. N/per acre for the Iowa site). We also analyzed fertilizer application at half of these typical rates.

Finally, we simulated two harvest regimes, one where the corn is harvested for silage (where 95 percent of the above-ground biomass is removed) and the other where corn is harvested for grain (where the "stover" is left behind to decompose on the field). These simulations enabled us to isolate the effect of the carbon added directly to the system in the form of compost, as opposed to total carbon inputs (which include crop residues).

5.2.4 Outputs

CENTURY is capable of providing a variety of output data, including carbon storage in soils, CO_2 emissions due to microbial respiration, and monthly potential evapotranspiration. The outputs we chose were carbon levels for each of the eight soil pools: structural carbon in surface litter, metabolic carbon in surface litter, structural carbon in soil litter, metabolic carbon in soil litter, surface pool, active pool, slow pool, and passive pool. Our output data cover the period from 1900 through 2030. In general, we focussed on the difference in carbon storage between a baseline scenario, where no compost was applied, and a with-compost scenario. We calculated the delta between the two scenarios to isolate the effect of compost application. Output data in grams of carbon per square meter were converted to MTCE by multiplying by area (in square meters).

To express results in units comparable to those for other sources and sinks, we divided the increase in carbon storage by the short tons of organics required to produce the compost.[21] That is, we express the factors as a carbon storage rate in units of MTCE per wet short ton of organic inputs (not MTCE per short ton of compost).

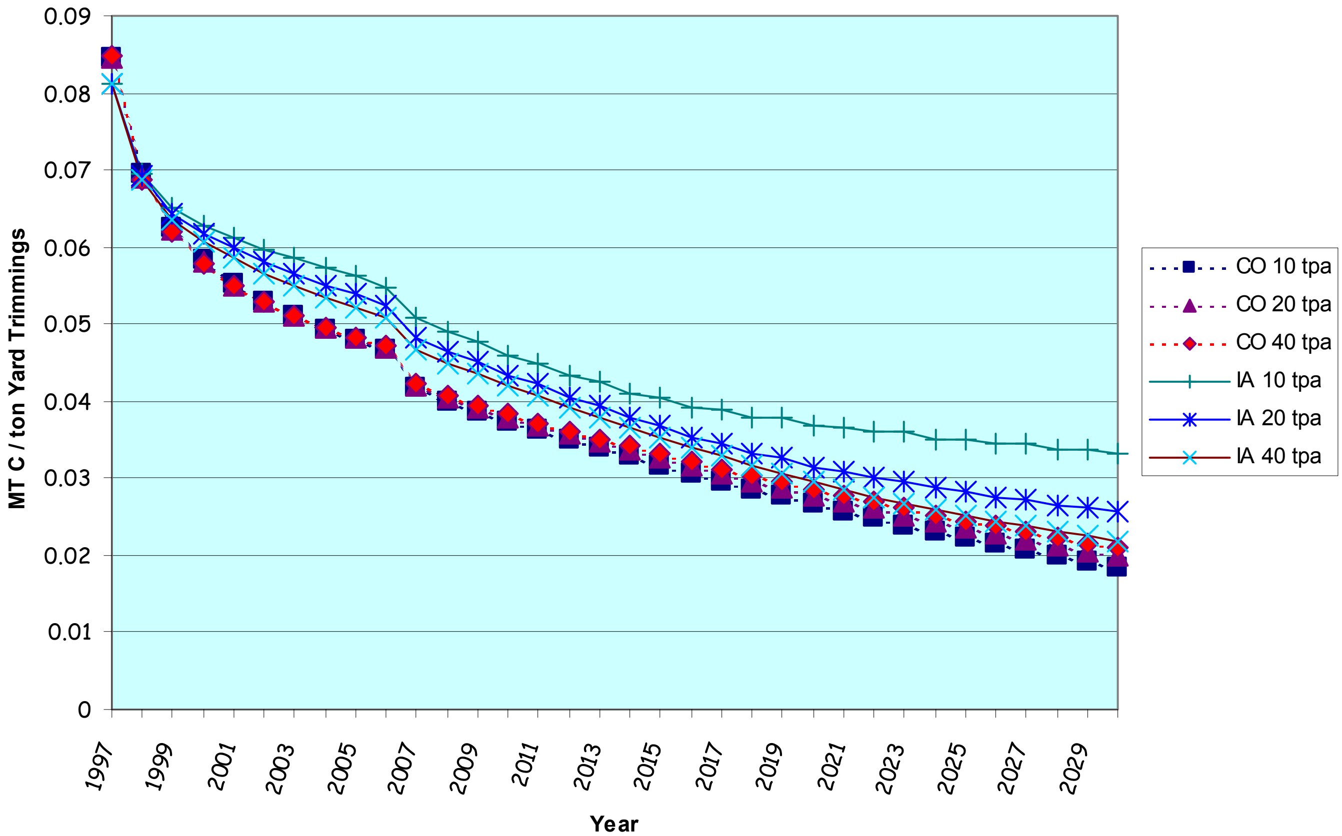
5.2.5 Results

The carbon storage rate declines with time after initial application. The rate is similar across application rates and frequencies, and across the site conditions we simulated. Exhibit 5-1 displays results for the Colorado and Iowa sites, for the 10-, 20-, and 40-ton per acre application rates. As indicated on the graph, the soil carbon storage rate varies from about 0.08 MTCE per wet ton organics immediately after compost application (in 1997) to about 0.02 MTCE per ton in 2030 (24 years after the last application in 2006).

[20] http://www.nrel.colostate.edu/PROGRAMS/MODELING/CENTURY/CENTURY.html

[21] We assume 2.1 tons of yard trimmings are required to generate 1 ton of composted yard trimmings. Thus, to convert the results in this report (in MTCE per wet ton yard trimmings) to MTCE per wet ton of compost, multiply by 2.1. To convert to MTCE per dry ton compost, multiply values in this report by 4.2 (assuming 50 percent moisture content).

Exhibit 5-1 Soil C Storage-CO and IA sites; 10, 20, and 40 tpa application rates



The similarity across the various site conditions and application rates reflects the fact that the dominant process controlling carbon retention is the decomposition of organic materials in the various pools. As simulated by CENTURY, this process is governed by first-order kinetics, i.e., the rate is independent of organic matter concentration or the rate of organic matter additions.

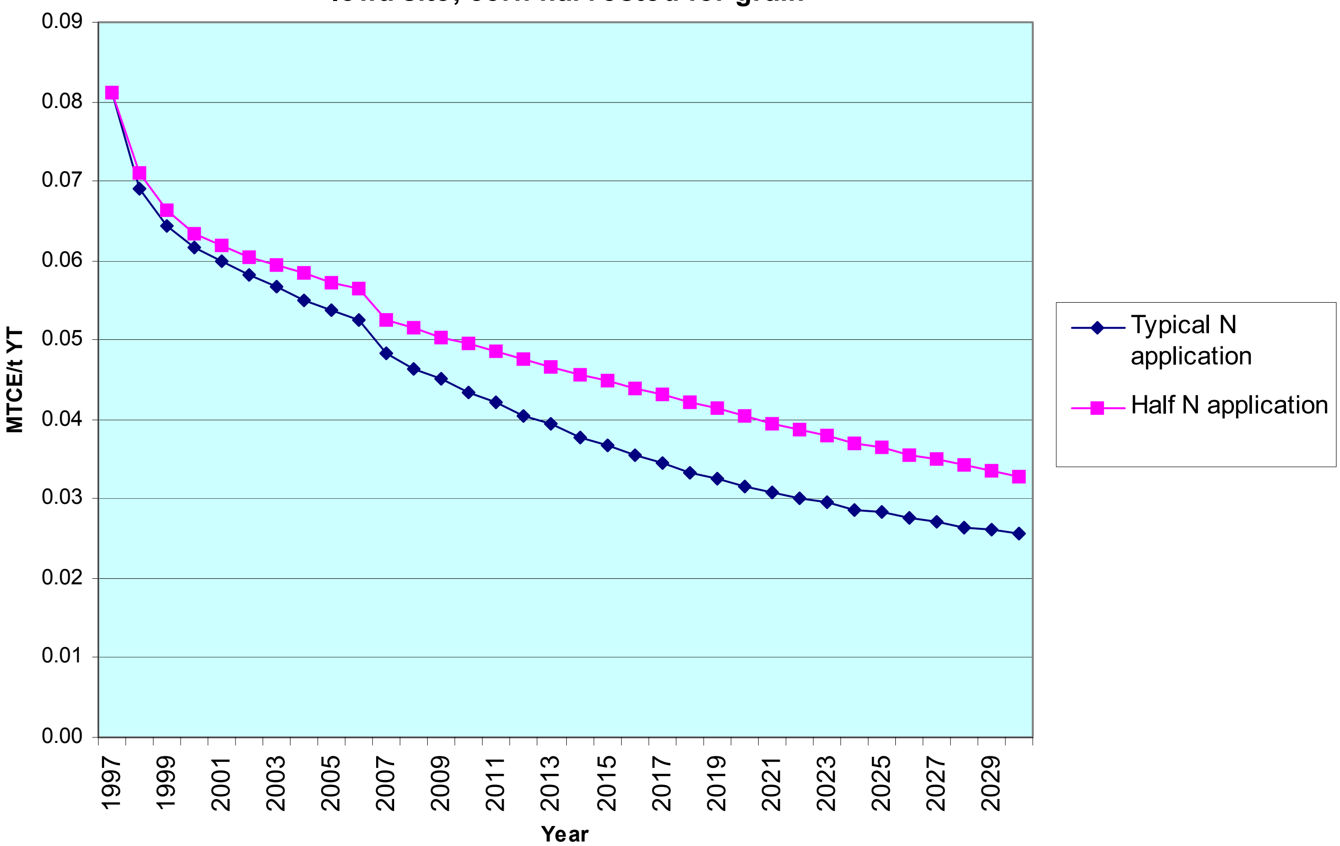
Several secondary effects, however, result in some variation in the carbon storage rate.[22] We had hypothesized that where a crop's demand for nitrogen exceeds its availability from other sources, mineralization of compost nitrogen can stimulate increased productivity. Simulation of this effect showed that where there is a shortage of nitrogen, compost application can result in higher productivity, which translates into higher inputs of crop residues to the soil. These higher inputs in turn increase the carbon storage rate per unit of compost inputs. This effect is a relatively modest one, however.

[22] In addition to the nitrogen fertilization effect, compost also affects moisture retention in soils, which in turn modifies the water balance relations simulated by CENTURY.

Exhibit 5-2 shows the carbon storage rate for the Iowa site and the effect of nitrogen fertilization. The two curves in the exhibit both represent the difference in carbon storage between (a) a with-compost scenario (20 tons per acre) and (b) a baseline where compost is not applied. The nitrogen application rates differ in the following ways:

- The curve labeled "Typical N application" represents application of 124 lbs. per acre, for both the compost and baseline scenario. Because the nitrogen added via compost has little effect when nitrogen is already in abundant supply, this curve portrays a situation where the carbon storage is attributable solely to the organic matter additions in the compost.
- The curve labeled "Half N application" represents application of 62 lbs. per acre. In this scenario, mineralization of nitrogen added by the compost has an incremental effect on crop productivity compared to the baseline. The difference between the baseline and compost application runs reflects both organic matter added by the compost and additional biomass produced in response to the nitrogen contributed by the compost.

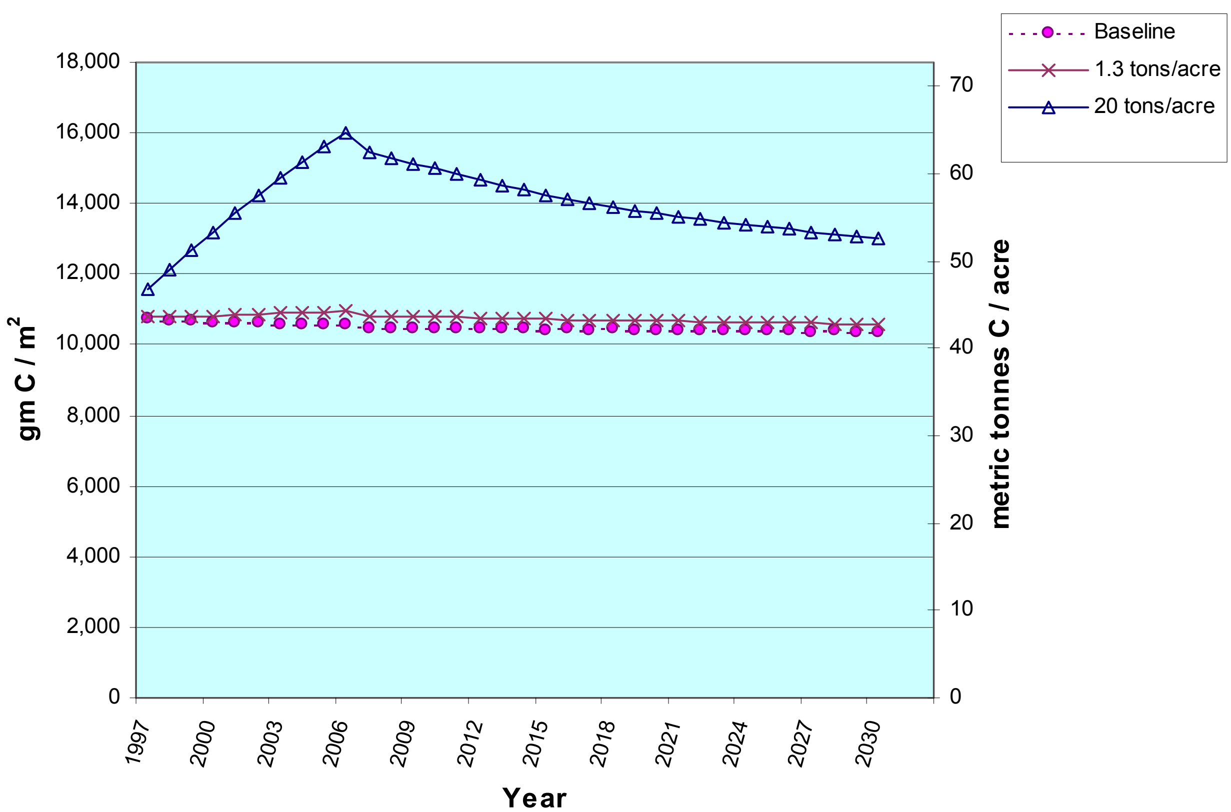
Exhibit 5-2
Incremental Carbon Storage as a function of Nitrogen Application Rate
Iowa site, corn harvested for grain



The difference in incremental carbon storage rates between the two fertilization scenarios is less than 0.01 MTCE per ton, indicating that the nitrogen fertilization effect is small. Note that this finding is based on the assumption that farmers applying compost also will apply sufficient synthetic fertilizer to maintain economic crop yields. If this assumption is not well-founded, or in situations where compost is applied as a soil amendment for road construction, landfill cover, or similar situations, the effect would be larger.

When viewed from the perspective of total carbon, rather than as a storage rate per ton of inputs to the composting process, both soil organic carbon concentrations and total carbon stored per acre increase with increasing application rates (see Exhibit 5-3). Soil organic carbon concentrations increase throughout the period of compost application, peak in 2006 (the last year of application), and decline thereafter due to decomposition of the imported carbon. Exhibit 5-3 displays total carbon storage (including baseline carbon) in soils on the order of 40 to 65 metric tons per acre (the range would be higher with higher compost application rates or applications with a longer term).

Exhibit 5-3 Total Soil C
Iowa site, corn harvested for grain



5.2.6 Incremental Humus Formation

The third of the four hypotheses describing the benefits of composting, as compared to alternative management methods, is predicated on incremental formation of stable carbon compounds that can be stored in the soil for long periods of time. CENTURY does not simulate this process, i.e., it does not allow for organic matter additions with high humus content to directly increase the magnitude of the passive pool. Therefore, we used a bounding analysis to estimate the upper and lower limits of the magnitude of this effect. In this analysis, we evaluated the amount of long-term soil carbon storage when organics are composted and applied to soil.

During the process of decomposition, organic materials typically go through a series of steps before finally being converted to CO_2, water, and other reaction products. The intermediate compounds that are formed, and the lifetime of these compounds, can vary widely depending on a number of factors, including the chemical composition of the parent compound. Parent compounds range from readily degradable molecules such as cellulose and hemicellulose to molecules more resistant to degradation, such as lignin, waxes, and tannins.

Composting is designed to promote rapid decomposition of organics, thus reducing their volume. Some evidence suggests that composting produces a greater proportion of humus than that typically formed when organics are left directly on the ground. The conditions in the two phases are different. The heat generated within compost piles favors ‘thermophilic’ (heat-loving) bacteria, which tend to produce a greater proportion of stable, long-chain carbon compounds (e.g., humic substances) than do bacteria and fungi that predominate at ambient soil temperatures.

Increased humus formation associated with compost application is a function of two principal factors:

(1) The fraction of carbon in compost that is considered “passive” (i.e., very stable); and

(2) The rate at which passive carbon is degraded to CO_2.

Estimates for the first factor are based on experimental data compiled by Dr. Michael Cole of the University of Illinois. Dr. Cole found literature values indicating that between 4 and 20 percent of the carbon in finished compost degrades quickly.[23] Dr. Cole averaged the values he found in the literature and estimated that 10 percent of the carbon in compost can be considered “fast” (i.e., readily degradable). The remaining 90 percent of carbon in compost can be classified as either slow or passive. We were not able to locate experimental data that delineates the fractions of slow and passive carbon in compost; therefore, we developed upper and lower bound estimates based on Dr. Cole’s professional judgement. He suggested values of 30 percent slow and 60 percent passive, and 45 percent slow and 45 percent passive for the upper and lower bounds on passive content, respectively.[24]

For the second factor, we chose a mean residence time for passive carbon of 400 years based on the range of values specified in the literature.[25]

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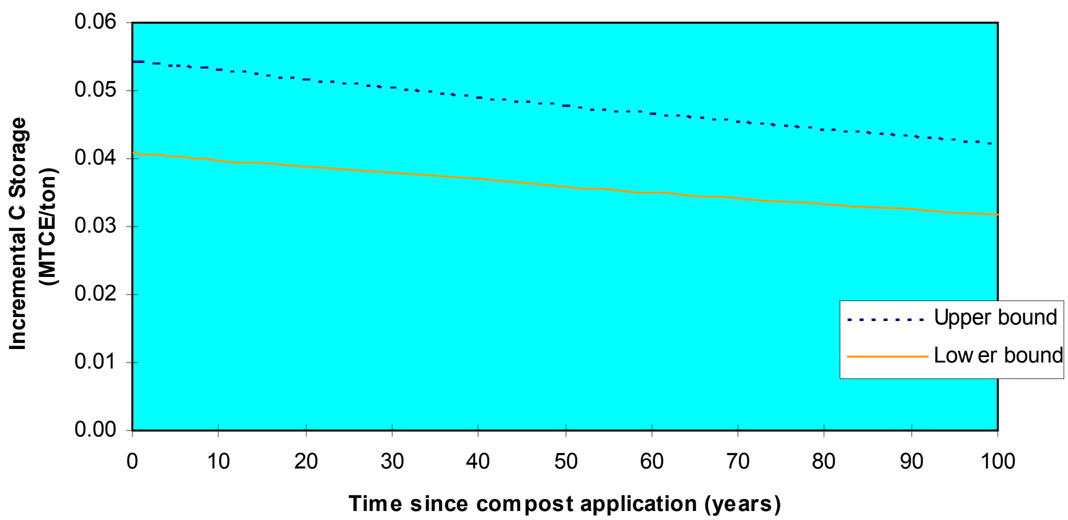
[23] Very little information is available on the characteristics of compost derived from yard trimmings or food discards. However, Dr. Cole found that the composition of composts derived from other materials is broadly consistent, suggesting that his estimates may be reasonably applied to yard trimmings or food scrap compost.

[24] We focussed only on the passive pool because (1) the CENTURY model does not allow for direct input of organic carbon into the passive pool, and (2) the model runs resulted in very little indirect (i.e., via other pools) formation of passive carbon. Although the first factor is also true for the slow pool, the second is not. Had we analyzed slow carbon in the same way as passive carbon, there would be potential for double-counting (see discussion in Section 5.3).

[25] Metherell et al. 1993, Brady and Weil 1999.

Combining the two bounds for incremental humus formation (60 percent passive and 45 percent passive), we estimated the incremental carbon storage implied by each scenario (see Exhibit 5-4).

Exhibit 5-4 Incremental Carbon Storage: MTCE/wet ton vs time



The upper bound on the incremental carbon storage from composting is more than 0.05 MTCE per ton of organics (shown in the top left of the graph); the lower bound is approximately 0.03 MTCE per ton (shown in the bottom right of the graph) after about 100 years. Incremental storage is sensitive to the fraction of carbon in compost that is passive but is not very sensitive to the degradation rate (within a 100-year time horizon, over the range of rate constants appropriate for passive carbon).

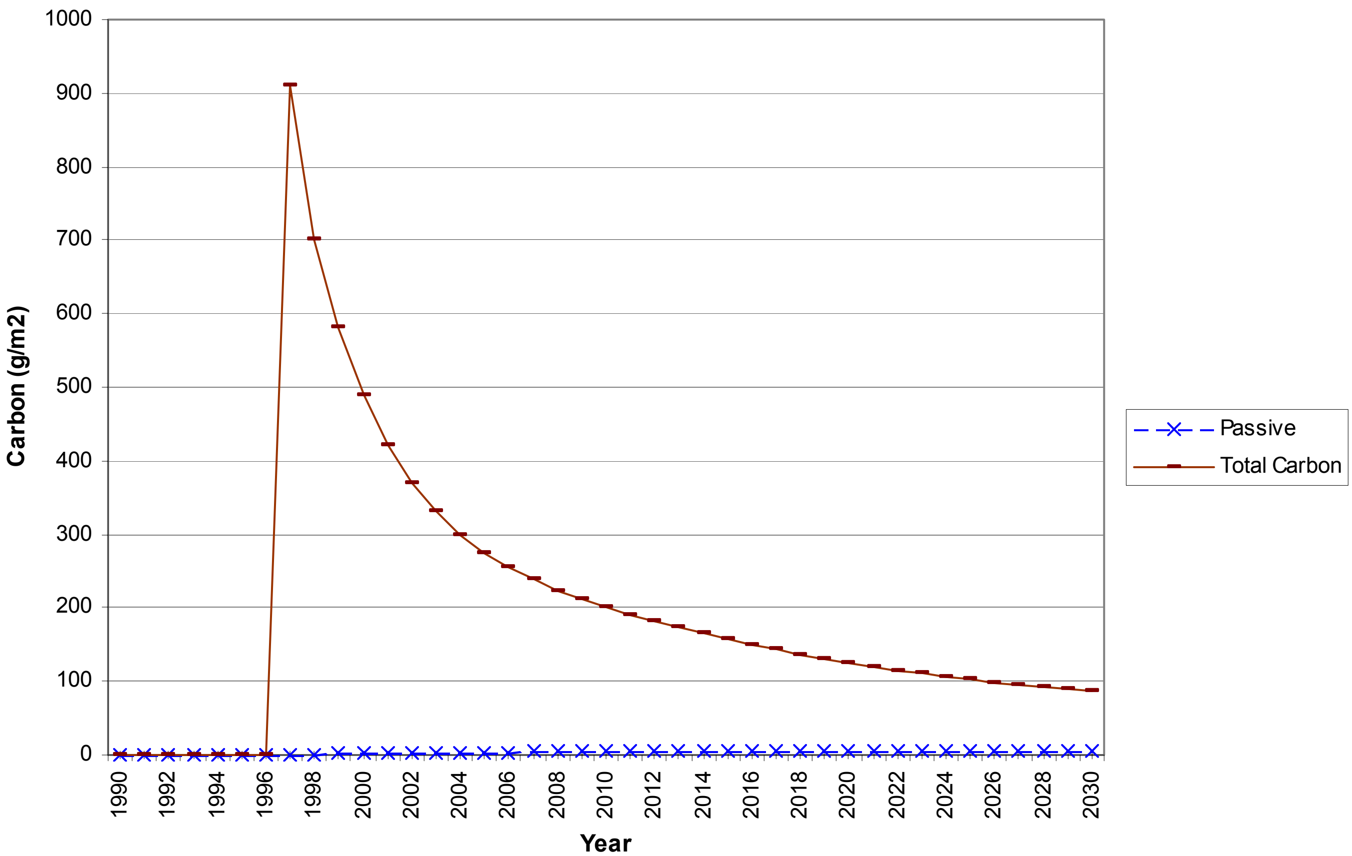
To select a point estimate for the effect of incremental humus formation, we took the average storage value across the two bounding scenarios, when time equals 10 years (i.e., approximately 2010). The resulting value is 0.05 MTCE/ton. The 2010 time frame was chosen for this analysis because the forest carbon estimates presented in Chapter 3 of this report are for the period ending in 2010.

5.3 NET GHG EMISSIONS FROM COMPOSTING

The approaches described in Section 5.2 were adopted to capture the range of carbon storage benefits associated with compost application. However, this dual approach creates the possibility of double counting. In an effort to eliminate double counting, we evaluated the way that CENTURY partitions compost carbon once it is applied to the soil.

To do so, we ran a CENTURY model simulation of compost addition during a single year and compared the results to a corresponding reference case (without compost). We calculated the difference in carbon in each of the CENTURY pools for the two simulations and found that the change in the passive pool represented less than 0.01 percent of the change in total carbon. Therefore, CENTURY is not adding recalcitrant carbon directly to the passive pool. Next, we graphed the change in the passive pool over time to ensure that the recalcitrant compost carbon was not being cycled from the faster pools into the passive pool several years after the compost is applied. As Exhibit 5-5 shows, CENTURY does not introduce significant increments (over the base case) of recalcitrant carbon into the passive pool at any time.

Exhibit 5-5 Difference in Carbon Storage Between Compost Addition and Base Case yearly application with 20 tons compost



Based on our analysis, it appears that CENTURY is appropriately simulating carbon cycling and storage for all but the passive carbon introduced by compost application. Because passive carbon represents approximately 52 percent of carbon in compost (the midpoint of 45 percent and 60 percent), we scaled the CENTURY results by 48 percent to reflect the proportion of carbon that can be classified as fast or slow (i.e., not passive).

Exhibit 5-6 shows the soil carbon storage and transportation-related emissions and sinks, and sums these to derive estimates of a net GHG emission factor, using the same sign convention as our broader analysis. A negative value denotes carbon storage; a positive value denotes emissions.

Summing the values corresponding to typical application rate and the 2010 time frame for soil carbon restoration (-0.02 MTCE/ton), increased humus formation (-0.05 MTCE/ton), and transportation emissions (0.01 MTCE/ton), the result is –0.05 MTCE/ton.[26]

[26] The addends do not sum to the total, due to rounding.

Exhibit 5-6
Net GHG Emissions from Composting
(In MTCE Per Short Ton of Yard Trimmings Composted)

Emission/ Storage Factor (for 2010)					
Soil Carbon Restoration			Increased Humus Formation	Transportation Emissions	Net Carbon Flux
Unweighted	Proportion of C that is not passive	Weighted estimate			
-0.04	48%	-0.02	-0.05	0.01	-0.05

5.4 LIMITATIONS

Due to data and resource constraints, this chapter does not explore the full range of conditions under which compost is managed and applied, and how these conditions would affect the results of this analysis. Instead, this study attempts to provide an analysis of GHG emissions and sinks associated with centralized composting of yard trimmings and food discards (henceforth, organics) under a limited set of scenarios. Our analysis was limited by the lack of primary research on carbon storage and CH_4 generation associated with composting. The limited availability of data forced us to rely on two modeling approaches, each with its own set of limitations. In addition, our analysis was limited by the scope of the report, which is intended to present life-cycle GHG emissions of waste management practices for selected material types, including food discards and yard trimmings.

5.4.1 Limitations of Modeling Approaches

Due to data and resource constraints, we were unable to use CENTURY to evaluate the variation in carbon storage impacts for a wide range of compost feedstocks (e.g., yard trimmings mixed with food discards, food discards alone). As noted earlier, resource constraints limited the number of soil types, climates, and compost applications simulated. The CENTURY results also incorporate the limitations of the model itself, which have been well documented elsewhere. Perhaps most importantly, the model's predictions of soil organic matter levels are driven by four variables: annual precipitation, temperature, soil texture, and plant lignin content. Beyond these, the model is limited by its sensitivity to several factors for which data are difficult or impossible to obtain (e.g., presettlement grazing intensity, nitrogen input during soil development).[27] The model's monthly simulation intervals limit its ability to fully address potential interactions between nitrogen supply, plant growth, soil moisture, and decomposition rates, which may be sensitive to conditions that vary on a shorter time scale.[28] In addition, the model is not designed to capture the hypothesis that, due to compost application, soil ecosystem dynamics change so that more carbon is stored than is actually being added to the soil (i.e., the multiplier effect).

[27] Parton, W., D.Schimel, C. Cole, and D. Ojima. 1987. "Analysis of Factors Controlling Soil Organic Matter Levels in Great Plains Grasslands." *Soil Sci. Soc. Am. J.* Vol. 51 (1173-1179).

[28] Paustian, K., W. Parton, and Jan Persson. 1992. "Modeling Soil Organic Matter in Organic-Amended and Nitrogen-Fertilized Long-Term Plots." *Soil Sci. Soc. Am. J.* Vol. 56 (476-488).

CENTURY simulates carbon movement through organic matter pools. Although the model is designed to evaluate additions of organic matter in general, to our knowledge it has not been applied in the past to evaluate the application of organics compost. CENTURY is parameterized to partition carbon to the various pools based on ratios of lignin to nitrogen and lignin to total carbon, not on the amount of organic material that has been converted to humus already. We addressed this limitation by developing an "add-on" analysis to evaluate humus formation in the passive pool, scaling the CENTURY results, and summing the soil carbon storage values. There is some potential for double-counting, to the extent that CENTURY is routing some carbon to various pools that is also accounted for in the incremental humus analysis. We believe that this effect is likely to be minor.

The bounding analysis used to analyze increased humus formation is limited by the lack of data specifically dealing with composts composed of yard trimmings or food discards. This analysis is also limited by the lack of data on carbon in compost that is passive. The approach of taking the average value from the two scenarios is simplistic but appears to be the best available option.

5.4.2 Limitations Related to the Scope of the Report

As indicated above, this chapter presents our estimates of the GHG-related impacts of composting food discards and yard trimmings. These estimates were developed within the framework of the larger report; therefore, our presentation of results, estimation of emissions and sinks, and description of ancillary benefits was not comprehensive. The remainder of this section describes specific limitations of our compost analysis.

As in the other chapters of this report, the GHG impacts of composting reported in this chapter are relative to other possible disposal options for yard trimmings (i.e., landfilling and combustion). In order to present absolute GHG emission factors for composted yard trimmings that could be used to compare composting to a baseline of leaving yard trimmings on the ground where they fall, we would need to analyze the home soil. In particular, the carbon storage benefits of composting would need to be compared to the impact that removal of yard trimmings has on the home soil.

As mentioned in Section 5.4.1, due to data and resource constraints, our analysis considers a small sampling of feedstocks and a single compost application (i.e., agricultural soil). We analyzed two types of compost feedstocks—yard trimmings and food discards—although sewage sludge, animal manure, and several other compost feedstocks also may have significant GHG implications. Similarly, we assumed that compost was applied to degraded agricultural soils, despite widespread use of compost in land reclamation, silviculture, horticulture, and landscaping.

This analysis did not consider the full range of soil conservation and management practices that could be used in combination with compost and the impacts of those practices on carbon storage. Some research indicates that adding compost to agricultural soils in conjunction with various conservation practices enhances the generation of soil organic matter to a much greater degree than applying compost alone. Examples of these conservation practices include conservation tillage, no tillage, residue management, crop rotation, wintering, and summer fallow elimination. Research suggests that allowing crop residues to remain on the soil rather than turning them over helps to protect and sustain the soil while simultaneously enriching it. Alternatively, conventional tillage techniques accelerate soil erosion, increase soil aeration, and hence lead to greater GHG emissions.[29]

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[29] R. Lal et al. 1998. *The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect* (Ann Arbor, MI: Sleeping Bear Press, Inc).

As is the case in other chapters, the methodology used to estimate GHG emissions from composting did not allow for variations in transportation distances. We recognize that the density of landfills versus composting sites in any given area would have an effect on the extent of transportation emissions derived from composting. For example, in states that have a higher density of composting sites, the hauling distance to such a site would be less and would require less fuel than transportation to a landfill. Alternatively, transporting compost from urban areas, where compost feedstocks may be collected, to farmlands, where compost is typically applied, potentially would require more fuel because of the large distance separating the sites.

Emission factors presented in this chapter do not capture the full range of possible GHG emissions from compost. Some of the nitrogen in compost is volatilized and released into the atmosphere as N_2O shortly after application of the compost. Based on a screening analysis, we estimated N_2O emissions to be less than 0.01 MTCE per wet ton of compost inputs and thus considered this effect to be negligible.

Addressing the possible GHG emission reductions and other environmental benefits achievable by applying compost instead of chemical fertilizers, fungicides, and pesticides was beyond the scope of this report. Manufacturing these agricultural products requires energy. To the extent that compost may replace or reduce the need for these substances, composting may result in reduced energy-related GHG emissions. Although we understand that compost is generally applied for its soil amendment properties rather than for pest control, compost has been effective in reducing the need for harmful or toxic pesticides and fungicides.[30]

In addition to the carbon storage benefits of adding compost to agricultural soils, composting can lead to improved soil quality, improved productivity, and cost savings. As discussed earlier, nutrients in compost tend to foster soil fertility.[31] In fact, composts have been used to establish plant growth on land previously unable to support vegetation. In addition to these biological improvements, compost also may lead to cost savings associated with avoided waste disposal, particularly for feedstocks such as sewage sludge and animal manure.

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[30] For example, the use of compost may reduce or eliminate the need for soil fumigation with methyl bromide (an ozone-depleting substance) to kill plant pests and pathogens.

[31] N. Brady and R. Weil. 1999. *The Nature and Properties of Soils* (Upper Saddle River, NJ: Prentice Hall).